EROSION AND SEDIMENT TRANSPORT IN A PROPOSED REGIONAL SANITARY LANDFILL

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SUMMARY

A regional sanitary landfill has been proposed for southern Puerto Rico. The proposed site consists of two parcels of land with a total surface area of 1.63 Km^2 (402.1 acres). As part of the studies and evaluations carried out to determine the environmental impact of the construction and operation of such facility, a study of erosion and sediment transport has been conducted. Six different rainfall events have been analyzed and the sediment yield for each one assessed. The rainfall events correspond to frequencies ranging from 1 year to 50 years with duration of 24 hours. The sediment yields for existing conditions were determined and compared to those after construction. Sediment yield comparisons showed that there would be augmentation in sediment yield for the disturbed conditions for all rainfall events. The results showed also that the generated runoff within the watershed would increase due to the vegetation removal and compaction of the soils. Sediment and erosion control structures were simulated with the computer program SEDIMOT II. Sedimentation ponds were rectangular in shape and had side slopes of 1 on 1. The result of the sedimentation pond simulations demonstrated that the excess sediment load generated within the landfill can be retained efficiently by the ponds. Trap efficiencies averaged 42.5 % which is adequate for the intended purposes. Peak flows could not be reduced significantly by these ponds which makes necessary the design of additional measures to control surface runoff from the site.

<u>Erosion</u>, Sediment, Solid Waste Landfill

Introduction

This study presents the results of an erosion and sediment transport analysis for a proposed sanitary landfill in the municipality of Salinas, Puerto Rico. The main objective of this study is to determine the production rate and transportation of sediments originated by the construction and operation of the sanitary landfill. This information can be used for the final design of the sediment control structures needed to achieve an environment safe construction phase and operation period for the facility.

The analysis carried out encompasses the determination of the rate of sediment production for various rainfall frequencies for 24 hour duration. The Modified Universal Soil Loss Equation (MUSLE) has been used to determine the erosion potential and sediment production of the proposed site for existing conditions. These results are the basis for comparisons with the sediment production rate after construction and during operation (disturbed conditions) of the sanitary landfill. Excess sediment production rate is then reduced by the implementation and use of sediment control measures and structures within the property. This approach has been carried out by means of the computer program SEDIMOT II (Sedimentology by Distributed Model Treatment) (Warner *et al*., 1989). This is a computerized model of surface mine hydrology and sedimentology developed by the University of Kentucky at the Department of Agricultural Engineering. The model was developed to predict the hydraulic and sediment response from surface mined lands for a specific rainfall event (single storm). Although the project under consideration is not a mine surface project, the landfill operation effect on the sedimentology of the area is very similar to that of a surface mine operation, thus the use of this procedure is justifiable.

SEDIMOT II is a single-event model based on the methodologies developed in each of four major areas: (1) rainfall component, (2) runoff component, (3) sediment component, and (4) sediment control component. The model predicts a storm hydrograph and a storm sediment graph for a user specified design storm. Both graphs can be routed along a stream to a given point of interest. Sediment distribution and total sediment load produced in a watershed are also part of the model output.

Six rainfall frequencies (1-, 2-, 5-, 10-, 25-, and 50-yr) have been used in the analysis. Existing and disturbed conditions were analyzed for each of the six 24-hr duration frequency. Sediment control structures (sediment ponds) were analyzed for the same frequencies and the results compared with present conditions. Recommendations are made for the mitigation of the sediment contamination over the surrounding environment.

Description of the Study Area

The study area is a watershed of 4.00 Km^2 (988.0 acres) located on the south coast of Puerto Rico at the municipality of Salinas. The parcels proposed for the sanitary landfill are within the drainage area and total 1.63 Km^2 (402.1 acres) of surface area. The site is bounded at the southern border by the PR-53 expressway. PR-706 runs northward along the western border of the property.

Two main drainage patterns can be identify within the drainage area. Both run southward from an elevation of 225 meters (738.2 ft) above mean sea level (msl) at the upper most portion of the watershed to about 35 meters (114.8 ft) (msl) at the outlet of the basin. The drainage area is a semi-enclosed basin within a narrow piedmont belt of hills that lie between the southern coastal plain and the Sierra de Cayey. The highest altitude of the drainage area is approximately 245 m (803.8 ft). Slopes within the lower part of the drainage area range between 4 and 7 percent and are considered mild. The upper most portion of the basin is steep with slopes of approximately 17 %. All streamflow within the basin is ephemeral. The predominate soils in the basin are listed in Table 1. Descalabrado clay loam and Jacana Clay are by far the most frequent soils within the boundaries of the watershed.

Table 1. Soils within the watershed boundaries.

Soil No.	Symbol	Soil Name and Brief Description	Hydrologic Group
1	DeE2	Descalabrado clay loam, 20 to 40% slopes, eroded	D
2	JaC2	Jacana clay, 5 to 12% slopes, eroded	D
3	JaB	Jacana clay, 2 to 5% slopes	D
4	PIB	Paso Seco clay, 0 to 5% slopes	D
5	DrF	Descalabrado Rock land complex, 40 to 60% slopes	D
6	DeC2	Descalabrado clay loam, 5 to 12% slopes, eroded	D
7	CIB	Coamo clay loam, 2 to 5% slopes	C

Source: U.S. Department of Agriculture, 1977

The Descalabrado series consists of well-drained, moderately permeable soils that are shallow to consolidated volcanic rock. These soils formed in moderately fine textured residuum derived from volcanic rocks. These soils have a moderate available water capacity and moderate shrink-swell potential. The runoff is medium to rapid. The soils are susceptible to erosion, and they have been in pasture and brush for many years. The Descalabrado clay loam is on mountain side slopes and is shallow to rock. The Jacana clays consist of moderately deep soils that are well drained and moderately slowly permeable. These soils formed in fine-texture sediment and residuum derived from volcanic rocks. They occupy foot slopes and low rolling hills. These soils have high shrink-swell potential and surface runoff is medium. These soils have severe limitations because of the hazard of erosion and poor workability. Good management and conservation practices are required to slow surface runoff and erosion.

Soil samples were collected at the site and their properties determined. A representative particle size distribution is presented in Figure 1. The soil classification according to the AASHTO is A-7-6 and according to the USCS is CH. The USDA texture is silty clay. Most of the surface of the watershed under study is covered by pasture and brushes. Small portions of woods can be found on the hills and along some natural drainage channels, but are very scarce.

Hydrology

The mean annual air temperature recorded by the National Oceanic and Atmospheric Administration (NOAA) for 1982 to 1988 at the Central Aguirre, which is located about three miles south of the proposed site, is 78.5 degrees Fahrenheit. Precipitation records obtained since 1930 indicate that the mean annual rainfall in the area is about 40 inches. Two seasons occur within the study area, a dry season that extends from December to April, and a wet season from May to November. The orographic effect of the Cordillera Central mountain range leads to hydrologic conditions typical of semiarid regions.

The hydraulic and sediment response of a watershed depends fundamentally on the rainfall temporal distribution pattern of a specific event. Techniques available to simulate this pattern in SEDIMOT II are: (1) depth-duration-frequency method, (2) SCS's type I and type II rainfall temporal distribution, and (3) Huff's method. In general, all of these methods use published rainfall data to develop dimensionless distributions that can be applied to the selected rainfall depth. SEDIMOT II has two options for the temporal rainfall distribution: (1) SCS's type I and II curves, and (2) input rainfall pattern. The first option consists of dimensionless curves developed by the SCS for 24-hour storms duration. For durations less than 24 hours the steepest portion of the curve is redistributed by a technique presented in Wilson et al. (1989).

The runoff component is divided into three minor components: (1) rainfall abstractions, (2) overland flow, and (3) channel flow. Rainfall abstractions considered by the model are the vegetative interception, depression storage, and infiltration. Evapotranspiration and groundwater movement are not considered because these abstractions are usually neglected in single-event models. The SCS Curve Number method is employed by the model to compute these abstractions.

The overland flow component is predicted using unit hydrographs techniques. Three options of hydrograph shape are available to the user: (1) forested, (2) agricultural, and (3) urban or disturbed. Each one represents the existing conditions of the basin surface. The peak flow of forested hydrograph shape is the lowest, followed by the agricultural and disturbed shapes. The channel flow component routes hydrographs to structures and among structures by Muskingum's routing procedure. This procedure employs input data such as travel time and a parameter related to the average velocity weighted by the distance between reaches and structures or among structures.

The watershed under study was divided into two subwatersheds to better describe the drainage pattern prevailing in the site. Subwatersheds were identified as Branch 1 and Branch 2. Branch 1 is located in the western portion of the basin and has a drainage area of 1.60 Km^2 (395.2 acres). Branch 2 is located in the east side of the basin with a drainage area of 2.4 Km^2 (592.8 acres). Due to the considerable

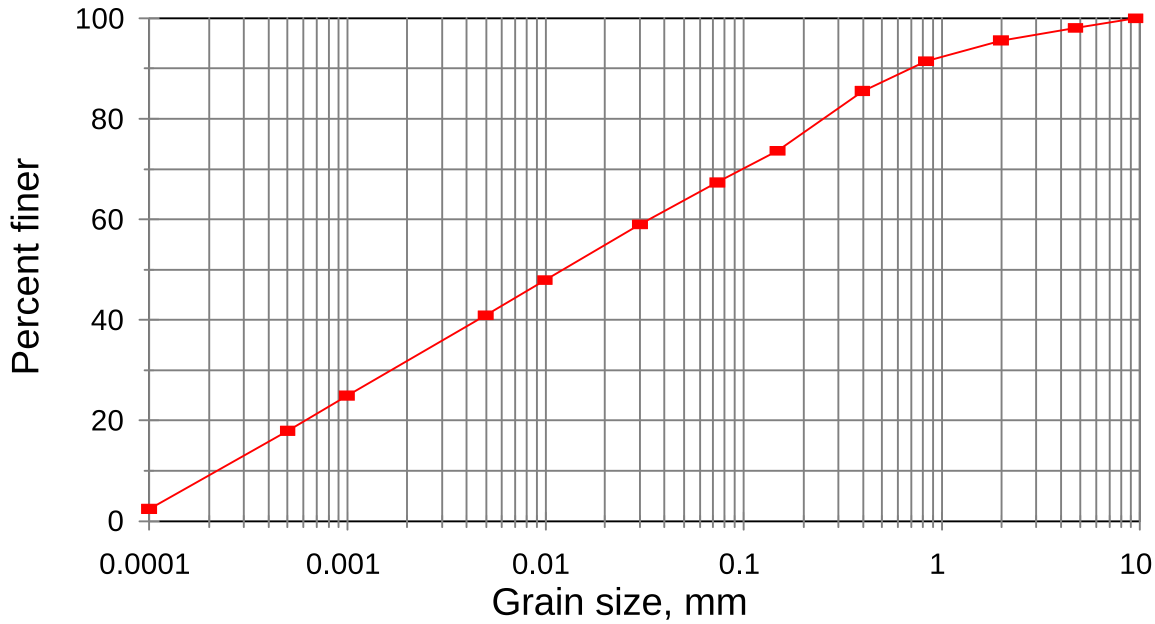

Figure 1. Particle size distribution

difference in slope within Branch 2, the slope was broken into two segments. Table 2 shows the physical characteristics of the watershed for each branch.

Table 2. Physical characteristics of the watershed.

	Branch 1	Branch 2	
	Segment 1	Segment 1	Segment 2
Length, m (ft)	1291.3 (4236.6)	504.8 (1656.2)	1319.9 (4330.7)
Slope, %	6.42	16.8	4.8
Area, Km^2 (acres)	120.5 (395.2)	45.2 (148.2)	135.5 (444.6)
Time of concentration, hr	0.41	0.45	0.45
Curve Number	80	80	80
Soil Factor	0.5	0.5	0.5
Control Protection Factor	1	1	1

Rainfall depths reported in Table 3 were used to analyze the existing conditions of the watershed. This condition is referred to hereafter as the undisturbed condition. The peak flows produced by the rainfall events with durations of 24 hours are presented in Table 4. They are also shown graphically in Figure 2. These results show an increase in the peak flows during the operation of the sanitary landfill. Increases range from 17.9 cms (632 cfs) for the 1-yr rainfall event to up to 77.1 cms (2722 cfs) for the 50-yr rainfall. The increase in peak flow is due to the removal of the vegetation and compaction of the soils during normal operation of the landfill facility. An appropriate designed sediment pond together with other mitigation measures should be enough to reduce the disturbed condition peak flows to adequate levels. The ponds assumed in this study were not designed for this purpose. As it can be seen from Figure 3, little attenuation is achieved with these ponds.

Table 3. Accumulated rainfall depths

Rainfall Frequency years	Rainfall Depth	
	mm	inches
1	91.4	3.60
2	119.4	4.70
5	167.6	6.60
10	193.0	7.60
25	236.2	9.30
50	264.1	10.40

Source: U.S. Weather Bureau, 1961

Table 4. Peak flows resulted from 24-hour rainfall events of various frequencies.

Rainfall Frequency	Peak Flows, cms (cfs)		
years	Undisturbed	Disturbed	Routed
1	17.1 (605.1)	35.0 (1,237.2)	34.4 (1,215.8)
2	27.3 (963.8)	54.3 (1,916.5)	52.9 (1,868.4)
5	45.4 (1,602.52)	88.9 (3,141.7)	87.2 (3,078.4)
10	55.1 (1,947.0)	107.5 (3,796.5)	104.8 (3,700.7)
25	71.8 (2,536.9)	139.1 (4,913.6)	135.7 (4792.6)
50	82.7 (2,919.7)	159.7 (5,641.7)	155.5 (5,490.9)

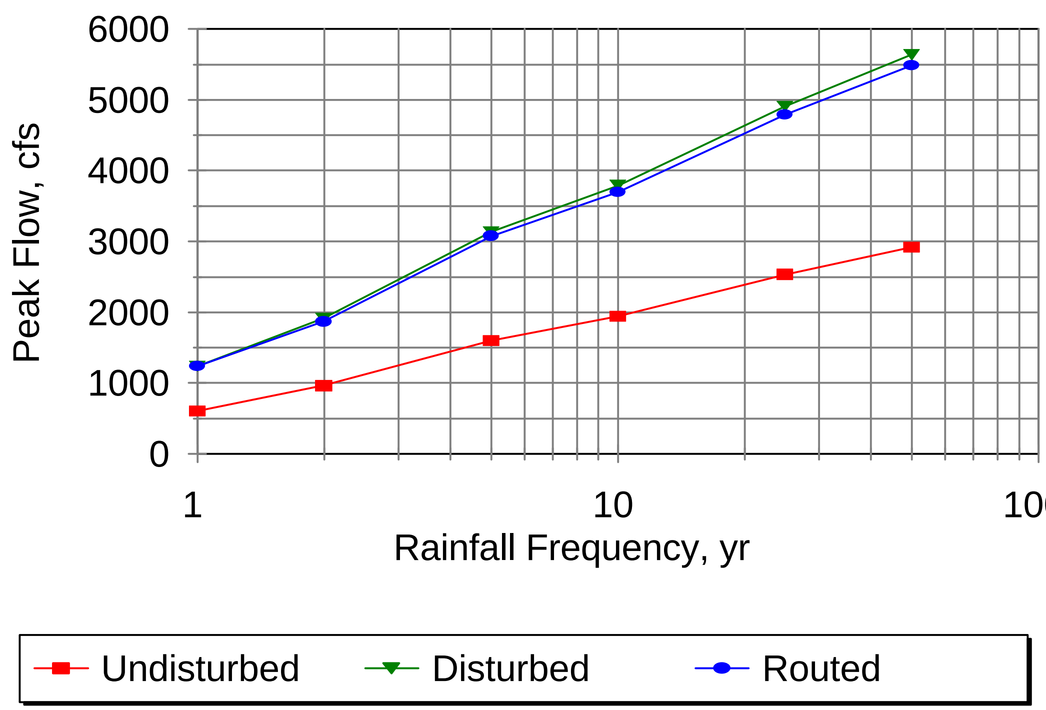

Figure 2. Peak flows for the undisturbed and disturbed conditions. Also shown are the peak flows routed through the ponds.

Sedimentology

The principal objective of the sediment component of SEDIMOT II is to determine the sediment yield produced in a watershed. Two subroutines are available to calculate sediment yield: (1) MUSLE (Modified Universal Soil Loss Equation), and (2) SLOSS (Soil LOSS routing in CREAMS model). In subroutine MUSLE, sediment yield is calculated using William's Modified Universal Soil Loss Equation (Wilson et al., 1989). In subroutine SLOSS, sediment yield is calculated using both detachment and transport capacity concepts. Particle detachment is calculated using the equations developed by Foster et al. (1981), and sediment transport capacity is calculated using Yang's unit stream power equation (Yang, 1972).

MUSLE is a modification of USLE (Universal Soil Loss Equation) by J. R. Williams (Wilson et al., 1989) to calculate soil loss during a storm event using the relationship

$$Y_y = 95\,(Q\ q_p)0.56\ K\ LS\ Cr\ Pe \qquad (1)$$

where Y_y is the sediment yield in tons, Q is the runoff volume in acre-feet, q_p is the peak flow rate in cubic feet per second, K is the erodibility factor, LS is the length-slope parameter, Cr is the cropping management factor, and Pe is the erosion control practice factor. The sediment produced is routed to the control structure (if any) by the sediment routing procedure developed by J. R. Williams (Wilson et al., 1989).

There exists a point in the specified particle size distribution curve entered by the user, where the fraction finer value is equal to the delivery ratio. The fraction finer value, $FF(D_p)$, is defined as the ratio of the mass of sediment finer than particle D_p to the total mass of sediment eroded in the watershed segment. The delivery ratio, DR, is defined as the ratio of mass of sediment delivered from upstream point to the total mass of sediment eroded in the watershed segment. The new particle size distribution is calculated as

$$FF_N(D_p) = 1 \qquad \text{if} \qquad D_p \geq D_{DR} \qquad (2)$$

and

$$FF_N(D_p) = FF_o(D_p) / DR \qquad \text{if} \qquad D_p < D_{DR} \qquad (3)$$

where $FF_N(D_p)$ and $FF_o(D_p)$ are the new and previous fraction finer distributions, respectively, and D_{DR} is the particle diameter corresponding to the fraction finer which is equal to DR.

SEDIMOT II can simulate three different sediment control structures, namely a pond, a vegetative filter, and a check dam structures. In addition, an option for a null structure allows the user to obtain the model output at a specific watershed outlet. In this study only the pond structure was considered. The performance of a sediment pond is evaluated using either of two models: (1) DEPOSITS (Detention Performance Of Sediment In Trap Structures), or (2) CSTRS (Continuous Stirred Type Reactors). The purpose of this structure is to intercept sediment-laden runoff and reduce the amount of sediment leaving the disturbed area to protect water bodies or adjacent properties.

The DEPOSITS model, presented in Wilson et al. (1989), was designed to consider the following factors in predicting the performance of detention ponds: (1) inflow sedimentgraphs; (2) inflow hydrographs; (3) hydraulic characteristics of the basin; (4) basin geometry; (5) particle size distribution of the sediment; and (6) viscosity of the flow. In DEPOSITS model, the flow is idealized as plug flow. It assumes the delivery of flow on a first in, first out basis. In other words, the inflow concentration is broken into plugs of concentration Co, where each plug marches through the pond without any mixing with the other plugs. The first plug will reach the outlet of the pond when the permanent pool (other plugs) is completely displaced. Detention time, portion of inflow sediment mass, and average water depth are determined for each plug. Trap efficiency and effluent concentrations are determined by calculating the amount of sediment which settles out in each of four layers, with settling velocities calculated from Stokes' law.

The sediment yield was determined for the six previous rainfall frequencies and the results are presented in Table 5. Figure 3 shows these results graphically. The sediment yield augments gradually as the frequency of the rainfall increases. Augmentations range from 70,561 tons of sediments for the 1-yr to 481,657 tons for the 50-yr rainfall event, respectively.

Table 5. Sediment yield within the watershed.

Rainfall Frequency, years	Sediment Yield, thousand tons		
	Undisturbed Condition	Disturbed Condition	Augmentation
1	106.763	177.324	70,561
2	189.843	309.628	119,785
5	371.139	594.288	223,149
10	482.468	767.602	285,134
25	693.109	1,093.774	400,665
50	842.346	1,324.003	481,657

The operation of the sanitary landfill will increase the sediment production within the drainage basin necessitating properly designed sediment ponds to capture the increased sediments. Transportation of augmented sediments out of the boundaries of the project would impact hydraulic balance downstream of the watershed outlet. On the other hand, total trap of sediments produced by the landfill operations would be detriment for downstream channels because the reduction in sediment input would bring the system out of hydraulic balance and excessive erosion of the channels would occur. Sediment flow needs to continue downstream of the watershed, but the excess produced by the sanitary landfill operations should be intercepted and prevented from flowing downstream, which can be accomplished by properly designed sediment ponds.

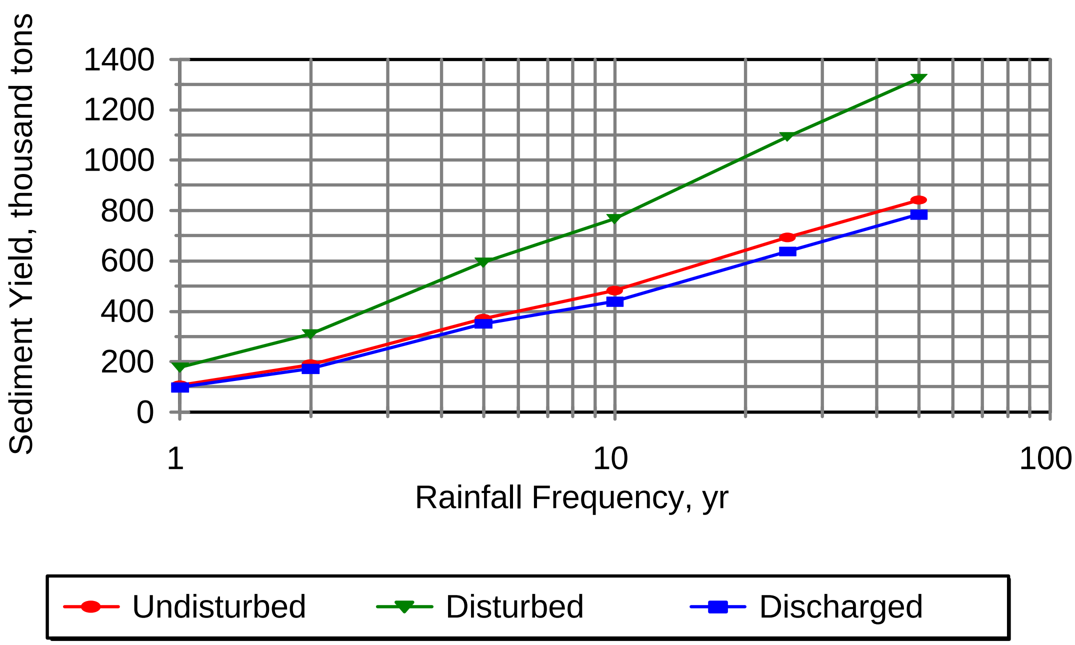

Figure 3. Sediment yield variation with rainfall frequency and pond performance.

Conclusions

The results of the study demonstrated that the proposed sanitary landfill operation will cause an increase in the sediment yield of the watershed. This situation would be detriment for the channel hydraulic balance downstream the watershed outlet if all sediment is retained or allowed to transport off the site. To mitigate this possible problem, different size sediment basins were analyzed and proved to perform satisfactory. Sediment excess can be trapped effectively within the boundaries of the proposed site maintaining the downstream channel hydraulic balance.

It is recommended that the design of these ponds takes into account the augmentation in peak flows. The peak flow should be attenuated within the ponds in such a manner that no increase in surface runoff will be produced or allow to flow off the site. Failure to attenuate the peak flows will break the hydraulic balance of the channels downstream increasing the available energy and channel erosion hazard. The figures provided herein may be used for the design of the ponds. Although the ponds simulated in this study did not attenuate peak flows properly, they proved satisfactory for sediment trapping purposes. This design should provide a sediment trap efficiency of about 40%.

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